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PROXIMATE AND ELEMENTAL COMPOSITION OF TEA EFFLUENTS OBTAINED FROM VARIOUS TEA PROCESSING FACTORIES IN KENYA

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ABSTRACT

Tea undergoes intricate processing in factories, generating substantial effluents that pose significant environmental challenges. This study explored the proximate and elemental composition of tea effluents obtained from various factories to determine their potential benefits, especially in agriculture and health. The proximate composition analysis revealed significant ($P<0.05$) variations in ash, crude fiber, carbohydrates, proteins, and lipids across samples from different factories. Notably, ash content in fluff samples from Mudete and Ogembo, and fly-off from Kionyo factories, is statistically comparable ($P>0.05$) but significantly higher than other samples ($P<0.05$). The cyclone fluff from the Kinoro factory exhibited significantly lower ash content than all other samples ($P<0.05$). The study further examined microelement minerals (calcium, potassium, magnesium, sodium, phosphorus) in tea samples, showcasing significant variations. The fluff sample from the Ogembo factory showed significantly higher calcium levels than others ($P<0.05$), while the cyclone sample from Mogogosiek displays significantly lower calcium concentrations than other samples ($P<0.05$). Regarding micronutrient/trace mineral elements, the fluff sample from the Gitambo factory has significantly higher Boron concentrations than other tea samples ($P<0.05$). Significant differences were observed in Cobalt concentrations, with cyclone fluff samples from Chelal and Momul factories showing significantly higher levels than others ($P<0.05$). The concentration of heavy metals (Aluminium, Chromium, Lead) in tea effluents varies significantly among samples from different factories ($P<0.05$). The cyclone fluff samples from Boito and Chelal factories and fluff samples Mogogosiek factory showed significantly higher Aluminium concentrations than others ($P<0.05$). The cyclone fluff sample from the Kinoro factory exhibited significantly lower Aluminium levels than others ($P<0.05$). Therefore, future research should delve into specific processes contributing to these variations, enabling tailored strategies for sustainable waste management in the tea industry. Moreover, adopting environmentally conscious approaches, informed by a nuanced understanding of metal concentrations in tea effluents, is imperative for ensuring the long-term viability of the tea industry and safeguarding environmental health.

Key words: Tea waste, micronutrients, macronutrients; heavy metals, nutritive value

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INTRODUCTION

Tea is the second most consumed beverage after water, with diverse economic, cultural, and health significance [1]. Processing tea leaves into the aromatic and flavourful infusion that millions enjoy involves intricate manufacturing processes. However, the production of this beloved beverage generates a substantial number of effluents, posing environmental challenges that require innovative solutions [2]. Sustainable management of tea processing wastes by converting them to valuable products may be the most feasible approach [3]. Currently, limited attention has been given to the detailed analysis of tea effluents' proximate and elemental composition and potential applications to manage these wastes sustainably [4]. This research sought to fill this void by comprehensively determining the various tea processing effluents' macro-, micro-, and trace elements and their implications for sustainable waste management.

Tea processing comprises a series of stages from plucking, withering, rolling, oxidizing, drying, sorting, and packaging. Each stage contributes to the production of flavours and smells characteristic of different tea varieties. However, this manufacturing process generates enormous waste, largely in the form of discarded tea leaves, stems, dust, cyclone, cyclone fluff, dry-off, fluff-dry mouth, and other by-products. Such wastes, if not managed correctly, creates environmental issues due to its organic nature and potential for pollution [5]. The waste created from tea manufacturing contains tremendous potential for effective reuse in agriculture, food, and nutrition industries. In agriculture, tea waste can serve as a beneficial organic fertilizer or soil conditioner, enhancing soil structure and boosting microbial activity. Additionally, the high nitrogen and potassium content in tea trash promotes plant growth and production while minimising the dependency on synthetic fertilizers, enhancing soil fertility, crop yield [6], and promoting sustainable farming practices [7]. Moreover, tea waste extracts have exhibited biopesticidal characteristics, presenting eco-friendly alternatives to conventional chemical pesticides for pest management in crop cultivation [8].

Furthermore, tea waste extracts exhibit antioxidant, antibacterial, and anti-inflammatory activities, rendering them effective for food preservation and nutritional and medicinal value [9]. The integration of tea waste extracts into food formulations has the potential to enhance shelf life, inhibit microbiological deterioration, and enhance goods with health-promoting elements. This approach aligns with consumer preferences for natural and sustainable food ingredients [10]. Besides, tea processing effluents hold the key to uncovering nutraceutical treasures to promote health [11, 12, 13]. The presence of these elements in tea effluents signifies the possibility of their nutraceutical applications, and health-promoting properties [9]. However, the potential nutraceutical value of elements in tea effluents remains largely unexplored. Understanding tea effluents' proximate and elemental composition opens avenues for their responsible and beneficial utilisation [14]. By transforming waste into a resource, the tea industry can mitigate its environmental impact and contribute to sustainable practices [3].

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MATERIALS AND METHODS

Collection and processing of tea waste samples

In this study, 25 tea waste samples (150-200 g), including fluffs, cyclones, cyclone fluffs, dry-offs, and fluff-dry mouths, were gathered from Kenyan processing factories and stored in clean brown glass bottles. The tea samples were transported to the Tea Research Institute (TRI, KARLO) laboratories at Timbilil Estate, Kericho (latitude 0°22'S, longitude 35°21'E, altitude 2180 meters above sea level) for analysis. The collected samples were oven-dried at 103°C to a constant weight using a Menmert oven (Germany) and finely milled with an electric blending device (Moulinex AR 1043, China) to reduce particle size. The resulting powdered samples were kept in desiccators before characterisation.

Proximate analysis

Determining nutritional components in plant materials is crucial in understanding their potential health benefits and applications [15]. This study used meticulous methods to quantify the tea waste samples' crude lipids, fibre, ash content, and carbohydrates.

Ash Content

The determination of ash content is crucial for understanding the inorganic residue left after the complete combustion of organic matter[16]. In this study, 6 g of pulverised samples were individually placed in labelled crucibles and ignited in a muffle furnace at 550°C for 6 hours [17], [18]. The resultant ashes were then carefully weighed after cooling in a desiccator at room temperature and expressed in percentage.

Crude Fiber

Crude fibre content was determined according to previously described procedures [18]. Briefly, 5 g of powdered materials were separately immersed in 200 ml of 1.25% H_2SO_4 and heated for 30 minutes in a hot water bath. Subsequently, the residues were filtered using a Buchner funnel, washed thrice with distilled water to eliminate acid residues, and boiled in 200 ml of 1.25% NaOH for 30 minutes. After further filtration and washing with petroleum ether, the residues were rinsed with 10% HCl and absolute ethanol to remove fats, dried, and expressed as a percentage.

Carbohydrate content

The assessment of carbohydrate content in tea waste was conducted using the Anthrone method outlined previously [19]. In this experiment, 100 mg of tea waste samples were subjected to 3-hour hydrolysis with 5 ml of 2.5 N HCL in a boiling water bath. After that, 20 % sodium carbonate was added, and the mixtures were dried and defatted. The acid concentration, temperature, and duration of the

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experiment were optimised to achieve complete hydrolysis of the carbohydrates in the study samples. The resultant solutions were centrifuged at 5000 g to obtain supernatant, from which 0.5- and 1-ml aliquots were aspirated and used for subsequent analysis. Besides, a standard glucose solution was serially prepared, yielding seven triplicate concentrations. The anthrone reagent was added to the mixtures, heated carefully in a water bath, cooled, and their respective absorbance values were measured at 630 nm using a double-beam spectrophotometer. Subsequently, a concentration-versus-absorbance (of the standard glucose solution) calibration graph was constructed using standardised data. The carbohydrate concentrations in the tea waste samples were interpolated from the standard curve.

Crude protein

The crude protein content was determined through the Kjeldahl method described previously [20] with slight modifications. The process involved three distinct steps.
Digestion: One-gram portions of each ground sample were individually weighed into separate digestion flasks. To ensure the accuracy of digestion parameters, a reagent blank and high-purity lysine hydrochloric acid were included. Components such as 15 g potassium sulfate, 0.04 g anhydrous copper sulfate, and 0.8 g alundum granules were added, followed by 20 mL of concentrated sulfuric acid. The digestion flasks were heated on mantles until white fumes cleared off the bulb, gently swirled, and further heated for 90 minutes in a fume chamber. Subsequently, the mixtures were allowed to cool to room temperature.

Distillation: A mixture of 15 mL hydrochloric acid and 70 mL water (V/V HCl) was accurately measured and added to the titration flask. For the reagent blank, 1 mL of acid and approximately 85 mL water were added, along with three drops of methyl red solution indicator. Gradually, along the side of the flask, 100 mL of 45% sodium hydroxide solution was introduced to raise the pH. The flask was connected to the distillation setup and distilled until at least 150 mL distillate was obtained in the titrating flask.

Titration: The excess acid being titrated with a standard 0.1M sodium hydroxide solution to the orange endpoint (color changing from red to orange to yellow). The volume was recorded to the nearest 0.01 mL (VNaOH). The reagent blank (B) underwent titration in the same manner.

Afterward, the following equation to determine the crude protein content in each sample required calculations were done using equations 1 (Eq.1) and 2 (Eq. 2).

$$\%\text{N (DM basis)} = \frac{[(\text{V HCL} \times \text{N HCL}) - (\text{V BK} \times \text{N NaOH}) - (\text{V NaOH} \times \text{N NaOH})]}{1.4007} \times \text{W} \times \frac{\text{LabDM}}{100} \ldots\ldots\ldots (\text{Eq. 1})$$

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Whereby, DM is dry matter; V NaOH = the volume of standard NaOH required for complete titration of the sample; V HCl = the volume of standard HCl transferred into the titration flask (ml); N NaOH = normality of the NaOH in use; N HCl = normality of the HCl in use; V BK = the ml standard NaOH required for titration with 1 ml standard HCl minus B. In this case, B = the standard NaOH ml required for titrating the reagent blank obtained by this procedure and distilled in 1 ml standard HCl; 1.4007 = milliequivalent nitrogen weight multiplied 100; W = the weight of the sample (g).
The percentage of crude protein was calculated as per equation:

$$\mathrm{CP(DM\ basis)} = \%\ \mathrm{N(DM\ basis)} \times \mathrm{F} \ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{Eq.}\ 2)$$

Where F = 6.25 [20]

Crude Lipid

The estimation of crude lipid content utilised the Soxhlet extraction method [18, 21],. Precisely, 10 g of powdered tea waste samples from various factories were carefully weighed and enclosed within a filter paper, forming a thimble. The thimble was subsequently covered with cotton wool and placed in an extraction column connected to a Liebig condenser. The lipids were extracted from the materials using 200 ml of n-hexane.

Elemental Analysis of Tea Waste Samples

The elemental composition of tea waste samples was investigated using a combination of energy-dispersive X-ray Fluorescence Spectroscopy (EDXRF)[22] and Atomic Absorption Spectrophotometry (AAS)[23] techniques. The EDXRF system employed an X-ray spectrometer with a radioisotope excitation source, specifically [^{109}Cd ($T_{1/2}$ = 453 days, and activity =10 mCi)]. Elements including manganese (Mn), copper (Cu), iron (Fe), Calcium (Ca), Sodium (Na), phosphorous (P), potassium(K) molybdenum (Mo), magnesium (Mg), zinc (Zn), copper (Cu), Cobalt (Co), Boron (B), Aluminium (Al), and lead (Pb) were quantified. One gram of each sample was pressed into 2-3 pellets of 300-1000 mg/cm² for analysis. The emitted X-rays, projected by the radioactive source, were discerned by a Si (Li) detector (EG&G Ortec, 30mm²×10mm sensitive volume, 25 µm Be window) boasting an energy resolution of 200 eV at the 5.9keV Mn Kα – line. Spectral data were collected using a Canberra S-100 multichannel analyser (MCA), and EDXRF quantification employed an acquisition time of 1000 seconds. The subsequent X-ray spectral analysis and quantification were executed utilising IAEA QXAS software (QXAS 1992) based on the Fundamental Parameters Method (FPM).

The AAS technique was deployed to quantify magnesium (Mg) and chromium (Cr) using an AAS equipment (Model: 210VGP; Scientific Equipment). The glassware was thoroughly cleaned using concentrated nitric acid, hydrochloric acid, and a detergent in deionised triple-distilled water before each analysis to ensure minimal

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contamination. Standard Cr and Mg stock solutions (1000 ppm) (Aldrich Chemical Co., Inc.) were used to prepare stock solutions for each analysis. Accurate volumes of stock solutions were transferred into clean volumetric flasks (100 mL capacity) and diluted with triple-distilled deionised water. Blank solutions, excluding the target elements, were employed to control for background noise.

RESULTS AND DISCUSSION

Proximate composition of the analysed tea samples

Proximate and elemental analysis of plant-based products helps to profile the chemical class and the elements they contain. This facilitates the determination of their nutritional and medicinal value and offers evidence-based information to optimize them for safety and optimal benefits [24]. It is worth noting that the concentration and type of various parameters often vary based on environmental, agroecological, climatic conditions, and processing conditions of the site where samples are obtained from or are handled [25].

Ash content is determined as an indicator of inorganic components, especially minerals in the plant sample or its products, and the digestibility of that plant material when consumed [4]. While some of these inorganic components may be nutritionally important, some of them can impact the stability of plant products and may cause toxicity [26]. The percentages of ash in fluff samples from Mudete, and Ogembo and fly-off from Kionyo factories were statistically comparable ($P>0.05$) but significantly higher than other samples ($P<0.05$; Table 1). On the other hand, the cyclone fluff from the Kinoro factory exhibited significantly lower ash content than those of all the other samples ($P<0.05$; Table 1). Notably, variations in ash content, particularly in fluff samples from Mudete, and Ogembo, and fly-off from Kionyo factories, reveal consistent, statistically comparable quantities, and signify their higher mineral-rich compositions. However, cyclone fluff from the Kinoro factory exhibited lower ash content, indicating potential disparities in processing methods or raw materials [4]. These findings underscore the need for nuanced investigations to unravel the factors contributing to such compositional differences, and the specific mineral elements and their potential applications.

Dietary fibre plays various biologically beneficial roles in the body by aiding digestion, absorption of nutrients, waste excretion, and amelioration of constipation, among others [27]. This study revealed significant differences, with cyclone fluff from the Chelal factory recording higher percentages of crude fibre than other samples ($P<0.05$; Table 1). The fly-off sample from the Kionyo factory had significantly lower crude fibre content than all the other samples ($P<0.05$; Table 1). Several factories showed no significant differences in crude fibre content, indicating similarities in proximate composition ($P>0.05$; Table 1). The higher percentages of crude fibre the

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cyclone fluff from the Chelal factory denote potential benefits to the body and may be a valuable source dietary fibre from this underutilised resource to supplement animal feeds, in a similar manner as previously reported [28]. The lower crude fibre content in the fly-off sample from the Kionyo factory implies that such wastes offer little benefits associated with dietary fibre to the body. Nevertheless, there is a need to delve deeper and understand factors contributing to the variations in crude fibre across various wastes generated by different factories. The observed uniformity in crude fibre content across factories underscores consistency in this proximate component and can be attributed to the use of raw materials from similar tea clones and probably similar processing procedures [27].

Plant-based lipids, carbohydrates, and proteins constitute crucial nutritional elements in any diet, playing dual roles in the body by contributing to both structural integrity and physiological functions [29]. When consumed in optimal amounts, these biologically significant molecules actively contribute to the promotion of health, support growth, and serve as defenders against or alleviators of diseases [30]. Analysis of total carbohydrates showed significant variations across samples, with the cyclone fluff from the Chelal factory displaying a significantly higher percentage than other samples ($P<0.05$; Table 1). Samples from the Gitambo factory (cyclone), Kinoro factory (drier fly-off), Ogembo factory (fluff), and Tombe factory (cyclone) had significantly lower carbohydrate content than others ($P<0.05$; Table 1). Higher carbohydrate content implies potential benefit to the body when consumed and the respective effluents may be a good reservoir for this organic matter. However, carbohydrate content in samples from Gitambo, Kinoro, Ogembo, and Tombe factories (Table 1) suggests lower organic matter composition [29]. These variations can be attributed to differences in environmental, climatic, and agroecological conditions of where the samples were obtained from, and their processing conditions [25].

Protein is crucial for various body functions, including hormone synthesis, growth, tissue repair, volemic balance, and metabolic catalysis, among others [31]. Plant products containing considerable amounts of crude protein are considered nutritionally beneficial and can play a role in modulating various body functions [31]. In this study, assessment of crude protein content revealed significant ($P<0.05$) differences, particularly with the cyclone fluff sample from the Chelal factory containing a higher percentage (Table 1), depicting its potential benefits. The significantly lower crude protein content in the fly-off sample from the Kionyo factory ($P<0.05$; Table 1) indicates variations in nitrogenous components across waste streams. The observed uniformity in crude protein content across the various factories underscores consistency in this proximate component, hence corroborating earlier research [18].

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The analysis of crude lipid content in the tea waste samples depicted notable variations, with significantly ($P<0.05$) higher percentages observed in waste samples from the Mogogosiek factory (cyclone and fluff), Momul factory (fluff), and Mudete factory (fluff) (Table 1). Notably, the cyclone fluff and fluff (Chelal factory) and fly-off (Kionyo factory) had significantly lower crude lipid content than other samples ($P<0.05$; Table 1). No significant differences in crude lipid content were observed in samples from different factories, indicating consistency in this proximate component ($P>0.05$; Table 1). These findings are consistent with earlier research in this domain, and further denote the potential applications of these wastes in pharmaceutics [32].

Concentration of macro and micronutrient mineral elements and heavy metals in the tea samples

Concentration of macronutrient mineral elements

Mineral elements play a pivotal role in a myriad of physiological processes essential for the proper functioning, growth, and development of the human system [33]. This interconnectedness extends to the realm of plant life, where the mineral content is intricately tied to soil characteristics [34]. This relationship between soil, plants, water sources, and human health underscores the need for a holistic approach to nutrition, acknowledging the interplay of factors from the ground up [35]. Moreover, the role of mineral elements in plants goes beyond mere nutritional support- they play an important role in combating various diseases, establishing a correlation between mineral content in the human body and specific health conditions [36]. Metalloenzymes, including antioxidant enzymes, exemplify this dependency, relying on minerals for their activity [13]. This intricate connection between minerals, disease resistance, and enzymatic activity emphasizes the critical need for a well-balanced intake of these elements, not only for individual health but also for broader societal well-being [13].

This study investigated microelement mineral concentrations (Ca, K, Mg, Na, P) in tea samples from various factories (Table 2), revealing notable variations. The Ogembo factory's fluff sample exhibited significantly higher Ca levels, while the Mogogosiek cyclone sample had significantly lower Ca concentrations. Fluff from the Gitambo factory displayed significantly higher K levels ($P<0.05$), contrasting with lower levels in fluff samples from Kionyo and Chelal factories and Kinoro's cyclone fluff (Table 2). Magnesium concentrations were significantly higher in Kionyo and Ogembo's fly-off and fluff, whereas Boito and Mogogosiek's cyclone fluff showed markedly lower Mg levels ($P<0.05$; Table 2). Sodium concentrations were significantly higher in cyclone samples from Momul and Mudete factories, with Chelal's fluff displaying significantly lower levels ($P<0.05$; Table 2). Certain cyclone fluff and fluff samples exhibited comparable sodium concentrations, emphasizing the need for tailored waste management strategies in the tea industry. These findings

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underscore the importance of understanding mineral composition variations across different tea processing units. Achieving consistent quality in tea production hinges on the precise management of the mineral element; for instance, the careful balance of Ca, K, and Mn proves pivotal in influencing flavor profiles, while sodium and phosphorus contribute to overall nutrient content [37].

Regarding phosphorus concentrations, significantly higher levels were observed in the fly-off from the Kionyo factory, while the cyclone fluff and fluff from the Boito factory, along with the cyclone from Chelal and Mogogosiek factories, exhibited significantly lower phosphorus concentrations than other samples ($P<0.05$; Table 2). The study highlighted insignificant differences in phosphorus concentrations for specific cyclone and fluff samples ($P>0.05$; Table 2), indicating potential variations in nutrient content based on tea processing methods.

The obtained findings shed light on the collective impact of the elements on quality and applicability of the tested wastes in soil enhancement, as a valuable organic amendment, contributing to soil fertility and plant growth, nutrition, and overall human health [38]. Besides, these findings correspond with the surging allure towards sustainable agricultural practices and the utilization of organic substances to augment soil vitality. The microelement composition variations among various samples from various factories and serve as a foundation for the refinement of quality control measures. Moreover, the presence of macroelements in sufficient quantities in the tea effluents valorizes them for potential applications in nutraceutical formulation and supplementations, owing to their health-promoting benefits [39].
Concentration of trace/micronutrient mineral elements

Determining the concentrations of Boron (B), Cobalt (Co), Copper (Cu), Iron (Fe), Manganese (Mn), and Zinc (Zn) provides valuable insights into the potential health and nutritional implications of tea consumption, in accordance with established literature [38]. These minerals play crucial roles in human physiology, and their existence in tea waste may have implications for the creation of health-promoting goods [32]. Conducting research in this domain could investigate the bioavailability of these minerals from tea waste and their potential influence on human health, thus paving the way for inventive methodologies in nutrition and well-being. In this study, variations in micronutrient concentrations were observed among different tea samples as shown in Table 3.

The fluff sample from the Gitambo factory displayed significantly higher levels of Boron (B) compared to other samples ($P<0.05$; Table 3). However, no significant differences ($P>0.05$) in B levels were found among fluff samples from the Ogembo, Mudete, and Boito factories, cyclone fluff from the Chelal factory, and cyclone from the Mogogosiek factory (Table 3). Cobalt (Co) concentrations varied significantly,

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with cyclone fluff samples from Chelal and Momul factories showing notably higher levels ($P<0.05$), while the fluff samples from Boito and Mogogosiek factories had significantly lower Co levels ($P<0.05$; Table 3). No significant differences were observed in Co levels among samples from Gitambo, Kinoro, and Kionyo factories ($P>0.05$; Table 3).

The analysis of Copper (Cu) levels revealed significantly higher concentrations in fluff samples from Tombe and Momul factories, whereas cyclone fluff samples from the Boito factory had significantly lower Cu levels ($P<0.05$; Table 3). Samples, including cyclone fluff samples from Chelal and Kionyo factories, fluff samples from Chelal, Mogogosiek, and Ogembo factories, drier fly-off from Kinoro factory, and fly-off samples from Kionyo factory, showed comparable Cu concentrations ($P>0.05$; Table 3).

Regarding Iron (Fe), the cyclone sample from the Gitambo factory contained significantly higher levels, while the fluff sample from the Boito factory had notably lower Fe concentrations ($P<0.05$; Table 3). The cyclone fluff samples from the Momul and Chelal factories, fluff from the Kionyo and Kinoro factories, drier fly-off from the Kinoro factory, and fly-off from the Kionyo factory, showed no significant differences in Fe levels ($P<0.05$; Table 3).

Manganese (Mn) concentrations varied significantly, with the cyclone fluff sample from the Chelal factory having higher levels, and the cyclone fluff sample from the Kinoro factory exhibiting lower concentrations ($P<0.05$; Table 3). Some samples, including cyclone samples from the Gitambo, Mudete, and Tombe factories, and fluff from the Tombe factory, showed no significant differences in Mn levels ($P>0.05$; Table 3). Moreover, the Zinc (Zn) concentrations were significantly higher in the Ogembo factory fluff samples, while the fluff and cyclone samples from Gitambo had notably lower concentrations than all other samples ($P<0.05$; Table 3). No significant differences in Zn levels were observed among cyclone fluff samples from Chelal and Kionyo factories, fluff samples from Chelal and Momul factories, and cyclone samples from Gitambo and Mudete factories ($P>0.05$; Table 3). Similarly, levels of Zn in samples from Momul, Mogogosiek, and Kionyo factories did not show significant differences ($P>0.05$; Table 3).

These findings highlight the diverse micronutrient compositions in tea samples from different factories, underscoring the need for targeted investigations into the factors contributing to these variations and their potential implications for human health and nutrition. Besides, our findings not only enhance our comprehension of tea waste elemental composition, but also open doors for additional investigation into the potential health advantages and possible harnessing and incorporation in nutraceuticals, fertilisers, among other important materials. The variation in these

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elements among samples and factories indicates a complex nature, prompting further examination of the specific processes and practices that contribute to these discrepancies, and their impacts of nutrition.

Concentration of metal and heavy metal elements

The study aimed to assess the concentration of Aluminium (Al), Chromium (Cr), and Lead (Pb) in various samples from different tea processing factories. The results showed the cyclone fluff samples from Boito and Chelal factories and fluff samples from Mogogosiek factory had significantly higher Al concentrations than others ($P<0.05$; Table 4). The cyclone fluff sample from the Kinoro factory exhibited significantly lower Al levels than others ($P<0.05$; Table 4). However, no significant differences were observed in Al concentrations among several samples, including fluff samples from Itumbe, Gitambo, Tombe, Kionyo, Kaptumo, Mudete, Momul, Ogembo factories, cyclone fluff samples from Kaptumo and Momul factories, drier fly-off from Kinoro, and fly-off from Kionyo factories, and cyclone fluff from Kaptumo and Mudete factories ($P>0.05$; Table 4).

In addition to Al, the study investigated Chromium (Cr) levels, revealing significantly higher concentrations in the fluff sample from Ogembo compared to other samples, while the cyclone from Mogogosiek showed significantly lower Cr amounts ($P<0.05$; Table 4). No significant differences were observed in Cr levels among fluff samples from the Boito, Gitambo, and Mudete factories and the drier fly-off from the Kinoro factory ($P>0.05$; Table 4). Similarly, Pb levels exhibited variations, with fluff samples from Ogembo and Boito factories having significantly higher concentrations than others ($P<0.05$; Table 4). In contrast, the cyclone fluff sample from the Chelal factory and fluff sample from the Kaptumo factory, cyclone samples from the Tombe and Mogogosiek factories, and fly-off sample from the Kinoro factory showed significantly lower Pb levels than other samples ($P<0.05$; Table 4). Notably, no significant differences were found in Pb levels among multiple samples ($P>0.05$; Table 4), emphasising the complex variations in heavy metal concentrations within different tea processing factory effluents.

The significant variations observed in Al, Cr, and Pb concentrations among different samples and factories underscore the complex nature of tea effluents and prompt the need for targeted interventions to address health and environmental concerns due to exposure to them [40]. Our study emphasizes the importance of understanding the specific processes contributing to these variations, to help formulate tailored strategies for sustainable waste management in the tea industry [3]. Besides, understanding of metal concentrations in tea effluents presented in this study provides a foundation for informed quality control measures and process optimization in the tea industry [41]. The interdisciplinary nature of our research necessitates imperative collaboration among environmental scientists, agricultural

researchers, nutritionists, and policymakers [42]. By integrating insights from diverse fields, the development of comprehensive strategies for sustainable tea waste management can be achieved. This aligns with the broader global agenda of attaining sustainability across numerous industries and fostering circular economies [43].

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study's findings show that the analysed tea waste samples from various Kenyan factories have varied proximate and elemental composition. The presence of high fibre, carbohydrate, lipid, and protein, micro- and macro-elements, in high concentrations in some samples, hold potential for applications in agriculture, energy production, and other industrial processes. Notably, the beneficial components of these wastes may be extracted and incorporated into nutraceuticals, fertilisers, among other applications. Also, this study emphasises the need for targeted interventions to address environmental concerns related to metal composition in tea processing effluents, especially Al, Cr, and Pb to avert potential negative health effects.

Future research should delve into the specific processes contributing to these variations, to enable the formulation of tailored strategies for sustainable waste management in the tea industry. With the growing global awareness of environmental sustainability and a shift towards circular economies, policymakers can leverage the insights gained from the proximate and elemental composition of tea effluents to enact regulations that promote responsible waste management.

Availability of data and materials

All data is presented within the manuscript; however, the authors may provide any additional information upon reasonable request.

Competing Interests

We, the authors, declare that we do not have any competing interests/conflicts of interest regarding this publication.

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Authors' contributions

Thaddeus Mangenya conceived the research idea which was fostered by Daniel Kariuki, Johnson Kinyua, Martin Obanda, and Simon Ochanda. Thaddeus Mangenya performed the experiments, analysed the data, and wrote the draft manuscript. Gervason Moriasi donated reagents, optimised the design and experimental methods, and reviewed the draft manuscript. Daniel Kariuki, Johnson

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Kinyua, Martin Obanda, and Simon Ochanda supervised the entire study. All authors reviewed and approved the final draft for submission and publication.

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Table 1: Proximate composition of tea samples from various factories

Sample	% Ash	Crude fibre (%)	% T-Carbs	Crude protein (%)	Crude Lipid (%)
BCF	4.88±0.11^{cdef}	14.16±0.18^{h}	4.68±0.06^{h}	15.34±0.20^{ijk}	1.63±0.02^{c}
BF	3.43±0.18^{lm}	14.46±0.71^{gh}	4.78±0.26^{gh}	15.68±0.82^{ijk}	1.66±0.09^{c}
CCF	4.20±0.00^{ghij}	25.02±1.19^{a}	8.55±0.42^{a}	26.06±1.28^{a}	1.21±0.02^{k}
CF	4.95±0.50^{bcd}	15.13±0.12^{efg}	5.02±0.04^{efg}	16.45±0.14^{fghi}	1.24±0.01^{jk}
GC	4.80±0.28^{cdef}	12.79±0.53^{ij}	4.19±0.19^{ij}	16.98±0.75^{ef}	1.46±0.07^{ef}
GF	4.08±0.25^{hijk}	12.19±0.21^{jkl}	3.97±0.07^{jkl}	16.13±0.30^{ghij}	1.38±0.03^{gh}
I.C.	2.95±0.21^{m}	14.45±0.27^{gh}	4.78±0.10^{gh}	19.34±0.38^{d}	1.66±0.03^{c}
IF	5.80±0.71^{a}	14.23±0.22^{h}	4.70±0.08^{h}	19.02±0.31^{d}	1.63±0.03^{c}
KCF	4.30±0.14^{fghi}	18.69±0.24^{d}	6.29±0.09^{d}	20.52±0.27^{c}	1.48±0.02^{def}
KF	4.25±0.07^{ghij}	21.08±0.30^{b}	7.15±0.11^{b}	23.26±0.34^{b}	1.68±0.02^{bc}
KNCF	1.73±0.11^{n}	13.15±0.19^{i}	4.31±0.07^{i}	17.50±0.27^{e}	1.50±0.02^{de}
KDFo	3.75±0.21^{jkl}	11.57±0.23^{l}	3.75±0.08^{l}	15.25±0.33^{k}	1.30±0.02^{ij}
KOF	3.10±0.14^{m}	12.56±0.35^{ijk}	4.10±0.13^{ijk}	16.66±0.50^{efg}	1.43±0.04^{fg}
KOFo	5.85±0.35^{a}	10.61±0.06^{m}	3.41±0.02^{m}	13.88±0.08^{l}	1.18±0.01^{k}
KNFo	4.45±0.07^{defgh}	12.55±0.16^{ijk}	4.10±0.06^{ijk}	16.64±0.23^{fg}	1.43±0.02^{fg}
MGC	3.90±0.14^{ijkl}	15.21±0.12^{ef}	5.05±0.04^{ef}	16.55±0.14^{fgh}	1.76±0.01^{a}
MGF	3.64±0.20^{kl}	15.00±0.06^{efg}	4.98±0.02^{efg}	16.30±0.07^{fghi}	1.73±0.01^{ab}
MCF	4.65±0.07^{defgh}	14.67±0.30^{fgh}	4.86±0.11^{fgh}	15.92±0.34^{ghijk}	1.69±0.04^{bc}
MMF	4.35±0.07^{fghi}	15.26±0.06^{ef}	5.07±0.02^{ef}	16.59±0.07^{fg}	1.76±0.01^{a}
MDC	4.20±0.00^{ghij}	20.58±0.18^{b}	6.97±0.06^{b}	22.69±0.20^{b}	1.64±0.09^{c}
MDF	5.43±0.11^{ab}	15.38±0.24^{e}	5.11±0.08^{e}	16.74±0.27^{efg}	1.78±0.03^{a}
OGF	5.85±0.35^{a}	11.91±0.12^{kl}	3.87±0.04^{kl}	15.73±0.17^{hijk}	1.35±0.01^{hi}
TBC	4.43±0.04^{efgh}	12.20±0.06^{jkl}	3.98±0.02^{jkl}	16.15±0.08^{fghij}	1.38±0.01^{gh}
TFDM	5.23±0.39^{bc}	19.40±0.06^{c}	6.55±0.02^{c}	21.34±0.07^{c}	1.54±0.00^{d}
TBF	4.58±0.25^{defgh}	12.79±0.18^{ij}	4.19±0.06^{ij}	16.98±0.25^{ef}	1.46±0.02^{ef}

The results are presented as $\bar{x} \pm SD$ for two replicate experiments. Means with different superscript letters within the same column are significantly different (P<0.05; One-Way ANOVA with Fisher's LSD post hoc test); % T-carbs: Percentage Total carbohydrates; Boito cyclone fluff; B.F.: Boito fluff; CCF: Chelal cyclone fluff; C.F.: Chelal fluff; G.C.: Gitambo cyclone; G.F.: Gitambo fluff; I.C.: Itumbe cyclone; IF: Itumbe fluff; KCF: Kaptumo cyclone fluff; K.F.: Kaptumo fluff; KNCF: Kinoro cyclone fluff; KDFo: Kinoro Drier fly-off; KOF: Kionyo fluff; KOFo: Kionyo fly-off; KNFo: Kionyo next to fly-off; MGC: Mogogosiek cyclone; MGF: Mogogosiek fluff; MCF: Momul cyclone fluff; MMF: Momul fluff; MDC: Mudete cyclone; MDF: Mudete fluff; OGF: Ogembo fluff; TBC: Tombe cyclone; TFDM: Tombe fluff dry mouth; TBF: Tombe fluff

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Table 2: The levels of Macronutrient mineral elements in the tea samples obtained from various factories

Sample	Macronutrient minerals elements (µg/g)				
	Ca	K	Mg	Na	P
BCF	0.18±0.01^{m}	1.70±0.06^{ghijk}	0.08±0.01^{n}	<dl	0.10±0.03^{k}
BF	0.25±0.01^{j}	1.63±0.06^{hijkl}	0.09±0.00^{m}	<dl	0.12±0.02^{jk}
CCF	0.41±0.02^{d}	1.99±0.65^{def}	0.20±0.01^{c}	0.88±0.75^{cd}	0.25±0.02^{cd}
CF	0.29±0.01^{gh}	1.46±0.05^{klm}	0.09±0.01^{m}	0.01±0.01^{i}	0.12±0.02^{jk}
G.C.	0.31±0.01^{g}	2.73±0.09^{b}	0.18±0.01^{d}	0.53±0.02^{h}	0.21±0.01^{ef}
GF	0.27±0.01^{hij}	2.98±0.10^{a}	0.15±0.01^{g}	0.54±0.02^{gh}	0.20±0.02^{f}
I.C.	0.39±0.02^{e}	2.21±0.07^{cde}	0.21±0.01^{b}	0.62±0.02^{efgh}	0.28±0.01^{ab}
IF	0.30±0.01^{g}	2.35±0.08^{c}	0.18±0.01^{d}	0.55±0.02^{gh}	0.25±0.01^{cd}
KCF	0.37±0.01^{e}	1.79±0.06^{fghi}	0.18±0.01^{d}	0.86±0.03^{cde}	0.22±0.01^{de}
K.F.	0.41±0.02^{d}	1.45±0.05^{klm}	0.18±0.01^{d}	0.92±0.07^{bcd}	0.20±0.02^{f}
KNCF	0.28±0.01^{hi}	1.47±0.05^{jklm}	0.09±0.01^{m}	0.52±0.02^{h}	0.14±0.03^{ij}
KDFo	0.26±0.01^{ij}	1.86±0.06^{fgh}	0.14±0.01^{h}	0.59±0.02^{fgh}	0.20±0.01^{f}
KOF	0.20±0.01^{lm}	1.78±0.06^{fghi}	0.09±0.01^{m}	0.62±0.06^{efgh}	0.16±0.02^{hi}
KOFo	0.83±0.03^{b}	1.93±0.06^{ef}	0.22±0.01^{ab}	0.70±0.03^{defgh}	0.29±0.01^{a}
KNFo	0.29±0.01^{gh}	1.85±0.06^{fgh}	0.12±0.00^{j}	0.59±0.02^{fgh}	0.17±0.02^{gh}
MGC	0.15±0.01^{n}	1.88±0.06^{ef}	0.08±0.00^{n}	<dl	0.10±0.03^{k}
MGF	0.21±0.01^{kl}	2.12±0.07^{cde}	0.10±0.00^{l}	<dl	0.13±0.02^{ij}
MCF	0.34±0.01^{f}	1.85±0.06^{fgh}	0.18±0.01^{d}	1.13±0.07^{ab}	0.19±0.02^{fg}
MMF	0.38±0.01^{e}	2.14±0.07^{cde}	0.18±0.01^{d}	1.23±0.08^{a}	0.21±0.01^{ef}
MDC	0.38±0.02^{e}	1.59±0.05^{ijkl}	0.19±0.01^{cd}	0.99±0.04^{abc}	0.21±0.01^{ef}
MDF	0.47±0.02^{c}	1.66±0.05^{ghijkl}	0.13±0.00^{i}	1.03±0.07^{abc}	0.20±0.01^{f}
OGF	0.88±0.03^{a}	1.47±0.05^{jklm}	0.23±0.01^{a}	0.73±0.05^{defgh}	0.26±0.01^{bc}
TBC	0.27±0.01^{hij}	1.68±0.05^{ghilk}	0.15±0.01^{g}	0.79±0.03^{cdefg}	0.19±0.02^{gh}
TFDM	0.34±0.01^{f}	1.33±0.05^{m}	0.17±0.01^{e}	0.84±0.03^{cde}	0.20±0.02^{f}
TBF	0.31±0.01^{g}	1.68±0.06^{ghijk}	0.16±0.01^{f}	0.81±0.03^{cdef}	0.20±0.02^{f}

The results are presented as $\bar{x} \pm SD$ for three replicate experiments. Means with different superscript letters within the same column are significantly different (P<0.05; One-Way ANOVA with Fisher's LSD post hoc test); BCF: Boito cyclone fluff; B.F.: Boito fluff; CCF: Chelal cyclone fluff; C.F.: Chelal fluff; G.C.: Gitambo cyclone; G.F.: Gitambo fluff; I.C.: Itumbe cyclone; IF: Itumbe fluff; KCF: Kaptumo cyclone fluff; K.F.: Kaptumo fluff; KNCF: Kinoro cyclone fluff; KDFo: Kinoro Drier fly-off; KOF: Kionyo fluff; KOFo: Kionyo fly-off; KNFo: Kionyo next to fly-off; MGC: Mogogosiek cyclone; MGF: Mogogosiek fluff; MCF: Momul cyclone fluff; MMF: Momul fluff; MDC: Mudete cyclone; MDF: Mudete fluff; OGF: Ogembo fluff; TBC: Tombe cyclone; TFDM: Tombe fluff dry mouth; TBF: Tombe fluff

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Table 3: Levels of micronutrient/trace mineral elements in tea samples from various factories

Sample	Micronutrient mineral elements					
	B	Co	Cu	Fe	Mn	Zn
BCF	1.29±0.07^{l}	13.07±0.64^{m}	22.35±1.13^{i}	28.60±1.42^{m}	0.06±0.00^{i}	13.92±0.69^{hi}
BF	2.06±0.10^{k}	13.63±0.68^{m}	23.53±1.18^{i}	5.91±0.30^{o}	0.07±0.00^{h}	12.54±0.63^{jk}
CCF	2.36±0.12^{jk}	34.73±1.74^{ab}	30.88±1.55^{cdef}	125.00±6.24^{cd}	0.14±0.00^{a}	7.12±0.36^{mn}
C.F.	3.20±0.16^{hi}	12.23±0.59^{m}	22.44±1.12^{i}	48.33±2.46^{l}	0.06±0.00^{i}	7.01±0.35^{mn}
GC	6.37±0.32^{c}	23.87±1.19^{jkl}	28.37±1.42^{gh}	185.00±8.89^{a}	0.12±0.00^{c}	8.24±0.42^{lm}
GF	15.5±0.79^{a}	24.60±1.25^{ijk}	30.60±1.54^{defg}	137.33±6.81^{b}	0.08±0.00^{g}	4.60±0.23^{o}
I.C.	9.08±0.46^{b}	23.63±1.21^{kl}	28.21±1.42^{gh}	106.00±5.29^{f}	0.13±0.00^{b}	4.14±0.21^{o}
IF	5.50±0.28^{d}	21.77±1.10^{l}	30.21±1.52^{defg}	97.67±4.73^{g}	0.08±0.00^{g}	7.26±0.36^{lmn}
KCF	3.06±0.15^{i}	31.33±1.57^{cde}	30.27±1.52^{defg}	91.43±4.57^{gh}	0.09±0.00^{f}	20.39±1.03^{d}
KF	3.57±0.18^{gh}	28.70±1.42^{fg}	30.32±1.52^{defg}	120.00±6.24^{cd}	0.08±0.00^{g}	6.46±0.33^{n}
KNCF	3.57±0.18^{gh}	25.70±1.32^{ijk}	27.65±1.39^{h}	64.37±3.21^{k}	0.04±0.00^{j}	19.05±0.96^{e}
KDFo	4.14±0.21^{f}	26.27±1.36^{hi}	30.58±1.53^{defg}	121.00±6.24^{cd}	0.07±0.00^{h}	15.15±0.76^{gh}
KOF	3.84±0.20^{fg}	25.77±1.27^{ijk}	29.58±1.49^{efgh}	88.97±4.46^{hi}	0.04±0.00^{j}	11.25±0.56^{k}
KOFo	5.76±0.29^{d}	25.87±1.27^{hijk}	30.40±1.53^{defg}	123.67±6.43^{cd}	0.09±0.00^{f}	16.50±0.83^{f}
KNFo	4.01±0.20^{f}	26.30±1.32^{hi}	28.83±1.45^{fgh}	80.73±4.05^{ij}	0.06±0.00^{i}	14.31±0.72^{h}
MGC	2.37±0.12^{jk}	13.53±0.68^{m}	22.16±1.11^{i}	18.00±0.89^{m}	0.06±0.00^{i}	16.22±1.10^{fg}
MGF	2.80±0.14^{ij}	13.63±0.68^{m}	22.39±1.13^{i}	28.57±1.46^{mh}	0.07±0.00^{h}	8.50±0.43^{l}
MCF	5.60±0.28^{d}	35.40±1.78^{a}	31.95±1.60^{cde}	118.00±6.24^{de}	0.11±0.00^{d}	17.45±0.88^{f}
MMF	3.75±0.18^{fg}	32.67±1.63^{bc}	37.60±1.89^{a}	138.67±7.37^{b}	0.11±0.00^{d}	6.99±0.35^{mn}
MDC	1.41±0.07^{l}	27.93±1.38^{gh}	32.07±1.61^{cd}	97.23±5.10^{g}	0.12±0.00^{c}	7.38±0.37^{lmn}
MDF	2.31±0.12^{k}	33.10±1.68^{bc}	31.81±1.60^{cde}	127.00±6.24^{c}	0.08±0.00^{g}	11.71±0.59^{jk}
OGF	2.45±0.12^{jk}	30.37±1.53^{def}	30.49±1.53^{defg}	85.47±4.29^{hi}	0.10±0.00^{e}	34.5±1.73^{a}
TBC	3.08±0.15^{i}	29.23±1.47^{efg}	32.61±1.64^{cd}	93.57±4.73^{gh}	0.12±0.00^{c}	21.80±1.10^{c}
TFDM	3.75±0.19^{gh}	31.20±1.59^{cde}	33.14±1.67^{bc}	75.13±3.78^{j}	0.13±0.01^{b}	26.59±1.34^{b}
TBF	4.59±0.23^{e}	31.87±1.63^{cd}	35.41±1.78^{ab}	111.67±5.69^{ef}	0.12±0.00^{c}	25.64±1.29^{b}

The results are presented as $\bar{x} \pm SD$ for three replicate experiments. Means with different superscript letters within the same column are significantly different (P<0.05; One-Way ANOVA with Fisher's LSD post hoc test); BCF: Boito cyclone fluff; B.F.: Boito fluff; CCF: Chelal cyclone fluff; C.F.: Chelal fluff; G.C.: Gitambo cyclone; G.F.: Gitambo fluff; I.C.: Itumbe cyclone; IF: Itumbe fluff; KCF: Kaptumo cyclone fluff; K.F.: Kaptumo fluff; KNCF: Kinoro cyclone fluff; KDFo: Kinoro Drier fly-off; KOF: Kionyo fluff; KOFo: Kionyo fly-off; KNFo: Kionyo next to fly-off; MGC: Mogogosiek cyclone; MGF: Mogogosiek fluff; MCF: Momul cyclone fluff; MMF: Momul fluff; MDC: Mudete cyclone; MDF: Mudete fluff; OGF: Ogembo fluff; TBC: Tombe cyclone; TFDM: Tombe fluff dry mouth; TBF: Tombe fluff

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Table 4: Concentration of Metal and Heavy metal elements in the study samples

Sample	Metal	Heavy Metals	
	Al	Cr	Pb
BCF	99.3±5.05^{ab}	1.51±0.08^{gh}	0.34±0.05^{hij}
B.F.	80.1±3.99^{fgh}	1.19±0.06^{kl}	0.68±0.09^{a}
CCF	101.4±4.97^{a}	0.77±0.04^{o}	0.19±0.03^{kl}
CF	89.27±4.46^{cd}	1.95±0.10^{ef}	0.32±0.04^{ij}
GC	93.8±4.69^{bc}	1.88±0.09^{f}	0.38±0.05^{ghi}
GF	70.43±3.52^{jkl}	1.27±0.06^{jk}	0.53±0.07^{bc}
I.C.	81.17±4.10^{fgh}	0.76±0.04^{o}	0.42±0.05^{efgh}
IF	72.43±3.61^{ijkl}	1.86±0.09^{f}	0.47±0.06^{cdef}
KCF	73.27±3.67^{ijkl}	0.95±0.05^{n}	0.41±0.05^{efgh}
KF	83.87±4.20^{defg}	1.45±0.07^{hi}	0.27±0.04^{jk}
KNCF	58.13±2.89^{m}	2.12±0.11^{d}	0.48±0.06^{cde}
KDFo	77.6±3.89^{ghi}	1.35±0.06^{ij}	0.39±0.05^{fghi}
KOF	68.73±3.42^{kl}	0.72±0.04^{o}	0.51±0.07^{cd}
KOFo	80.93±4.05^{fgh}	2.42±0.12^{c}	0.41±0.05^{efgh}
KNFo	67.43±3.42^{l}	2.06±0.10^{de}	0.16±0.02^{l}
MGC	88.97±4.46^{cde}	0.17±0.01^{p}	0.19±0.03^{kl}
MGF	101.4±4.97^{a}	0.68±0.03^{o}	0.37±0.05^{ghi}
MCF	82.93±4.14^{defg}	0.99±0.05^{mn}	0.43±0.05^{defg}
MMF	81.03±4.05^{fgh}	2.76±0.14^{b}	0.41±0.05^{efgh}
MDC	70.57±3.57^{jkl}	0.64±0.03^{o}	0.32±0.04^{ij}
MDF	75.23±3.78^{hijk}	1.22±0.06^{jkl}	0.46±0.06^{cdefg}
OGF	82.23±4.14^{efg}	3.11±0.16^{a}	0.61±0.08^{ab}
TBC	70.47±3.39^{jkl}	<dl	0.19±0.03^{kl}
TFDM	77.13±3.88^{ghij}	1.62±0.08^{g}	0.51±0.06^{cd}
TBF	84.90±4.25^{def}	2.30±0.12^{c}	0.38±0.05^{ghi}

The results are presented as $\bar{x} \pm SD$ for three replicate experiments. Means with different superscript letters within the same column are significantly different (P<0.05; One-Way ANOVA with Fisher's LSD post hoc test); BCF: Boito cyclone fluff; B.F.: Boito fluff; CCF: Chelal cyclone fluff; C.F.: Chelal fluff; G.C.: Gitambo cyclone; G.F.: Gitambo fluff; I.C.: Itumbe cyclone; IF: Itumbe fluff; KCF: Kaptumo cyclone fluff; K.F.: Kaptumo fluff; KNCF: Kinoro cyclone fluff; KDFo: Kinoro Drier fly-off; KOF: Kionyo fluff; KOFo: Kionyo fly-off; KNFo: Kionyo next to fly-off; MGC: Mogogosiek cyclone; MGF: Mogogosiek fluff; MCF: Momul cyclone fluff; MMF: Momul fluff; MDC: Mudete cyclone; MDF: Mudete fluff; OGF: Ogembo fluff; TBC: Tombe cyclone; TFDM: Tombe fluff dry mouth; TBF: Tombe fluff

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